2.1 Fotosynthese en chemosynthese

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3.1 Where does the energy for life come from?

All life on Earth is dependent on the energy that can be fixed into carbohydrates by **autotrophic** organisms. An autotroph is able to make its own food by forming organic substances from simple inorganic molecules. In marine ecosystems, the autotrophs are either **photosynthetic** or **chemosynthetic**. Photosynthetic organisms capture the Sun's energy, whereas chemosynthetic organisms are able to use the energy in chemicals that are dissolved in the water.

Photosynthesis can only take place in the sunlit upper layer of the ocean. About 90% of all marine life is therefore found in this area. The ability of the chemosynthetic organisms to produce carbohydrates is an important adaptation to living in extreme conditions. The hydrothermal vents where they are found have no light so photosynthesis is not possible. Until the vent communities were discovered in the 1970s, it was thought that the only way in which energy would reach the lower parts of the ocean was when organisms died and fell to the bottom.

Other organisms have to obtain their energy by feeding on the autotrophs. These are known as **heterotrophic** organisms or consumers. The **primary productivity** of an ecosystem relates to how much energy is fixed into **carbohydrates** (new organic matter). The most productive ecosystems per unit area are estuaries, swamps and marshes. However, the most productive ecosystems overall are the oceans, because they cover such a high proportion of the Earth's surface. Over a billion people rely on marine ecosystems for their food. Although we tend to think that increased productivity is always an advantage, this is not always true. Marine dead zones are areas where the productivity has reached such a peak that the ecosystem becomes unbalanced. Eventually oxygen levels are reduced and there is very little life.

KEY TERMS

Autotroph (autotrophic): an organism that can capture the energy in light or chemicals and use it to produce carbohydrates from simple molecules such as carbon dioxide

Photosynthesis (photosynthetic): the process of using light energy to synthesise glucose from carbon dioxide and water

Chemosynthesis (chemosynthetic): the production of organic compounds by bacteria or other living organisms using the energy derived from reactions with inorganic chemicals

Heterotroph (heterotrophic): an organism that cannot make its own food and instead relies on consuming other organisms; all animals, fungi and protozoans are heterotrophic, as well as most bacteria

Primary productivity: the rate of production of new biomass through photosynthesis or chemosynthesis

Carbohydrate: organic compounds occurring in living tissues that contain carbon, hydrogen and oxygen, for example starch, cellulose and sugars; carbohydrates can be broken down in the process of respiration to release energy

3.2 Productivity

Primary productivity is the rate of production of new biomass (living material) by autotrophic organisms through either photosynthesis or chemosynthesis (Figure 3.1). It allows light or chemical energy to be fixed into useable organic molecules, and as such is the basis of all food chains and food webs. In all ecosystems illuminated by the Sun, the main way in which energy is fixed is through photosynthesis. On land the majority of photosynthesis is carried out by green plants, but in the oceans it is mainly carried out by **phytoplankton**. Most of these tiny algae are single-celled and simply float with the current in water. As well as the phytoplankton there are also much larger algae (macroalgae), such as kelp and rooted plants called seagrass. These organisms are all photoautotrophs: they make their own food using light energy. You will learn about the adaptations of each of these producers in Chapter 8.

Photosynthesis

Photosynthesis is a process in which the inorganic compounds carbon dioxide and water are combined to produce glucose. Glucose is a useable organic compound. Oxygen is produced as a byproduct.

carbon dioxide + water → glucose + oxygen

The energy to do this comes from sunlight and must be absorbed by pigments in the plants or algae.

KEY TERM

Phytoplankton: microscopic photosynthetic organisms that live in the upper, sunlit layers of water

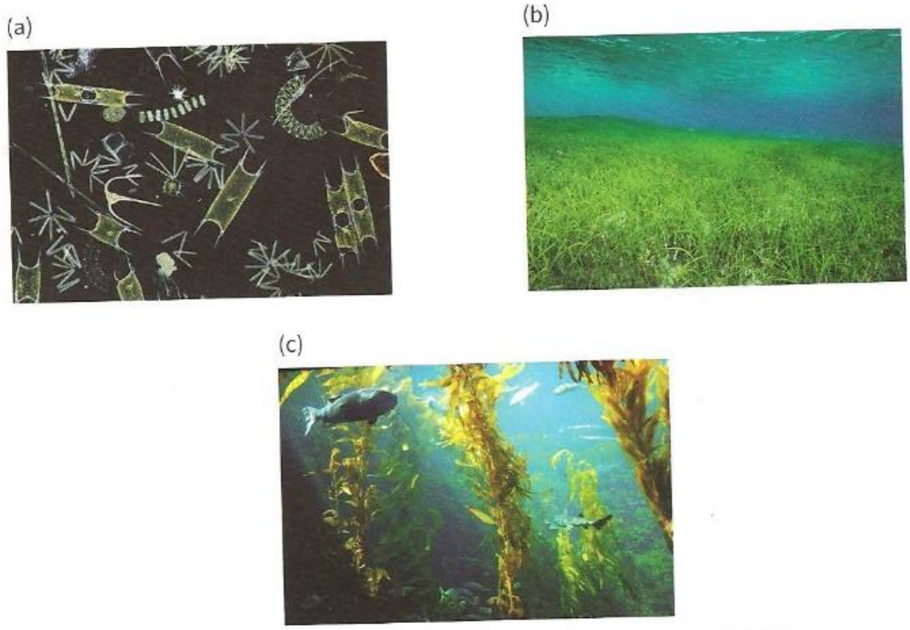


Figure 3.1. Important producers in marine ecosystems: (a) phytoplankton; (b) seagrass; (c) kelp.

The most common pigment is **chlorophyll**, which is found in organelles called chloroplasts (Figure 3.2). You can read more about the different pigments needed for photosynthesis in Chapter 8.

KEY TERM

Chlorophyll: a pigment found in plants and algae that is used to absorb sunlight for photosynthesis

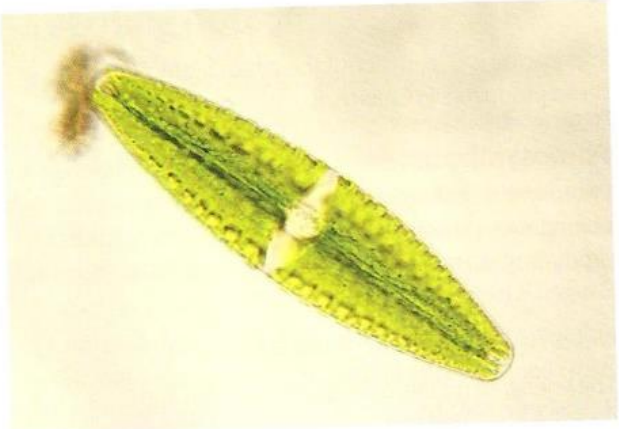


Figure 3.2. Single-celled alga with green chloroplasts visible.

Factors affecting photosynthesis

The rate of photosynthesis can be affected by several different factors. These include:

- nutrients
- amount of light
- temperature
- concentration of carbon dioxide.

In a marine environment, the most important factors are likely to be the availability of nutrients and light.

Temperature and carbon dioxide

Clearly there is always an abundance of water, and the water contains dissolved carbon dioxide. Although temperature affects the rate of the reactions taking place during photosynthesis, the temperature of the ocean is much more stable than air temperature on land.

Nutrients

Algae and plants both need nutrients in the form of mineral ions in order to grow. A lack of a particular nutrient therefore affects the rate of productivity of new biomass because it affects the rate of growth. Nutrient availability is discussed in more detail in Chapter 4.

Light

The layer of the ocean that has enough light for photosynthesis is relatively thin compared with the total depth. This sunlit zone is called the photic zone and all photosynthesis must take place here (Figure 3.3). This means that the vast majority of the biomass in the open ocean is contained within the upper 200 m of water.

Water both absorbs and scatters the sunlight. The amount of light reflected will depend on the state of the water. When there are waves, more light is reflected because the waves act like lenses and focus the light. When the light penetrates the surface of the water it is refracted because light travels more slowly in water than in the air. Finally, solid particles within the water also scatter and absorb the light. The availability of light within the water and methods to measure the light penetration are discussed further in Chapter 8.

The absorption of sunlight by the water also increases the temperature of the water. When the temperature increases, the molecules of water have more kinetic energy and are moving more quickly so the water is less dense and therefore more buoyant than cold water. The thin layer of warm water floats on top of the colder deep water and the transition between the two is called the **thermocline**. It can also be referred to as a **pycnocline**, which is simply related to the different densities of the layers rather than the temperature. There is little mixing between the two layers because a source of energy (such as wind) is needed to push the warm water down. This is very important to the phytoplankton as it keeps them floating near the surface where they have access to light.

KEY TERMS

Thermocline: a boundary between two layers of water with different temperatures

Pycnocline: a boundary between two layers of water with different densities

Deep chlorophyll maximum: the maximum concentration of chlorophyll below the surface of a body of water

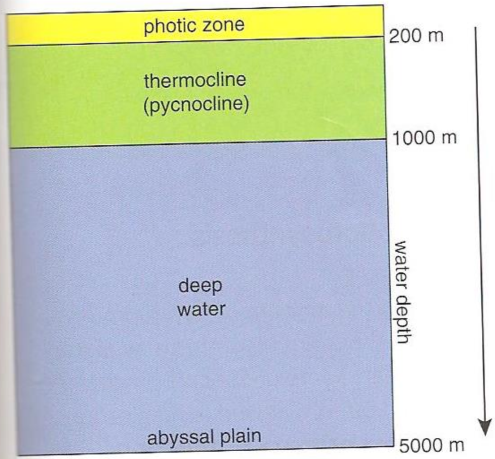


Figure 3.3. Layers of water in the ocean.

Without the thermocline, there would be much more mixing of the water and currents would carry the phytoplankton down and away from the light. This would reduce the rate of photosynthesis and therefore the productivity. However, the thermocline also prevents nutrient-rich water from mixing with the upper layers and therefore limits the productivity. Generally the deeper the water the higher the nutrient levels but the lower the light. There is normally a point near the thermocline where the productivity is highest as there is enough light for photosynthesis and enough nutrients for growth. This level is known as the **deep chlorophyll maximum** (DCM) because it is the area with the highest concentration of chlorophyll.

The light varies with the seasons, particularly at high latitudes. In spring the average length of the day and the intensity of light both increase. This is clearly an advantage in terms of photosynthesis, and productivity is therefore higher in spring and summer than it is in winter. Often it is nutrient availability that limits the rate of photosynthesis in spring and summer, and light which limits it during autumn and winter.

SELF-ASSESSMENT QUESTIONS

1 State the two ways in which new biomass is produced in the ocean.

2 Explain why ocean productivity is limited to the first 200 m in depth.

Chemosynthesis

There are some ecosystems, such as those found around hydrothermal vents, where light is not available for productivity. Chemosynthesis is a process where carbon dioxide is turned into useable organic molecules using the energy stored in dissolved chemicals. The chemicals dissolve in heated water in the undersea crust as it makes its way back to the surface to emerge from the vents. Chemoautotrophs are species of bacteria that are able to make their own food using chemical energy. There are several species of chemosynthetic bacteria, including *Beggiatoa* and *Thiothrix* species. Each species uses different chemicals as their energy source and produces different sugars. One common pathway is:

hydrogen sulfide + oxygen + carbon dioxide → sugar + water + sulfur

Chemosynthetic bacteria were first discovered in hydrothermal vents in the ocean floor in 1977. The vents are found at depths varying from around 2000 m in the Galapagos

Ridge to 7700 m in the Mid-Atlantic Ridge. Clearly at these depths there is no light, there are no phytoplankton and therefore there can be no photosynthesis. Chemosynthesis is the only way in which life is possible in such an inhospitable environment. The species able to survive here are all examples of **extremophiles**, which means that they are able to survive very harsh conditions. At these vents there is extremely high pressure, as well as water temperatures that can vary from 2 °C to 400 °C.

Chapter 2 discusses the symbiotic relationship between giant tube worms (*Riftia* species) and chemosynthetic bacteria (Figure 3.4). Up to 75% of animal species at hydrothermal vents depend on mutualistic relationships with chemosynthetic bacteria for at least some of their food. For example, mussels at these vents have mutualistic bacteria living in their gills but also filter feed.

Figure 3.4. Giant tube worms at hydrothermal vents have a symbiotic relationship with chemosynthetic bacteria.

KEY TERMS

Extremophile: an organism that is adapted to survive extreme temperature, pressure, salinity or pH

Respiration: the process by which all living things release energy from their food by oxidising glucose

Similarities and differences between photosynthesis and chemosynthesis

Both photosynthesis and chemosynthesis use carbon dioxide and require an energy source to produce sugars. In photosynthesis, oxygen is produced as a byproduct whereas in chemosynthesis the byproducts vary depending on the chemicals that are used, although sulfur is often produced. There is therefore only one possible equation for photosynthesis compared with several different equations for chemosynthesis. In both processes the sugars produced are used to provide metabolic energy through **respiration**, or built up into the other chemicals needed by the organism

SELF-ASSESSMENT QUESTIONS

3 Explain why the organisms living at hydrothermal vents are called extremophiles.

4 Copy and complete Table 3.1 to compare photosynthesis and chemosynthesis in ocean ecosystems.

	process	
feature	chemosynthesis	photosynthesis
energy source		
products		
type of organism		
main location in ocean		

Table 3.1. Photosynthesis and chemosynthesis.

Respiration

Respiration is the process by which all living things release the chemical energy stored in organic molecules such as carbohydrates. This energy is then used to carry out all the different metabolic reactions within the organism. Aerobic respiration requires a supply of oxygen and glucose and produces carbon dioxide and water.

glucose + oxygen → carbon dioxide + water

As well as the useable energy the organism needs, respiration produces heat energy, which is lost to the environment.

The link between photosynthesis and respiration

Primary productivity is the amount of new biomass made by the producers, but not all of this is available for the consumers to eat. Some of the carbohydrate produced is not stored but is oxidised in respiration to provide energy. **Gross primary production** (GPP) is the amount of energy that primary producers are able to fix in a given length of time and within a given

8.1 The foundation of marine life

All food chains and food webs in the world's oceans ultimately require a source of energy. There are two main sources of energy for these food webs: light from the Sun and hydrogen sulfide from deep-sea hydrothermal vents. All food webs begin with organisms that can trap or fix this energy and convert it into energy stored in organic chemicals such as **carbohydrates**. This ability to take inorganic molecules and use energy to create organic molecules is called **autotrophic nutrition**. The roles of **primary producers** are to fix carbon and provide **habitats** for other organisms. They also shape environments by fixing the substrate and providing shelters and **nursery grounds** for other species of animal. Photosynthesis also produces oxygen gas, without which organisms would be unable to **respire**. Without producers in an **ecosystem**, there would be no food chain, very little atmospheric oxygen and a loss of habitat for many animals. This chapter looks at the process and importance of primary productivity in marine ecosystems.

KEY TERMS

Carbohydrate: organic compounds occurring in living tissues that contain carbon, hydrogen and oxygen, for example starch, cellulose and sugars; carbohydrates can be broken down in the process of respiration to release energy

Autotroph (autotrophic): an organism that can capture the energy in light or chemicals and use it to produce carbohydrates from simple molecules such as carbon dioxide

Primary producer: organisms that produce biomass from inorganic compounds, in almost all cases these are photosynthetically active organisms

Habitat: the natural environment where an organism lives

Nursery ground: important habitats of oceanic water where young fish and other species find food and shelter from predators, for example mangroves

Respiration: the process by which all living things release energy from their food by oxidising glucose

Ecosystem: the living organisms and the environment with which they interact

8.2 The basics of productivity

The majority of primary productivity in the world's seas and oceans is the result of **photosynthesis**. It is the process by which green plants, photosynthetic protoctists such as **diatoms** and **dinoflagellates**, and photosynthetic bacteria such as **cyanobacteria**, gain their energy from sunlight. Organisms that convert light energy into chemical energy in the form of organic chemicals are the basis of most of the world's food webs. Without photosynthesis, there would be almost no way to bring energy into the planet's ecosystems and life on Earth would be all but extinct.

Photosynthesis requires light energy to be trapped by pigments such as chlorophyll. This trapped energy is then used by the producer to produce glucose and oxygen (a byproduct) from carbon dioxide and water. Carbon is fixed into organic compounds and energy is taken from sunlight and converted into chemical energy in the form of organic compounds. The chemical process occurs in many steps and is controlled by a large number of **enzymes**.

The basic equation for photosynthesis is:

$$6\ CO_2 + 6\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2$$

carbon dioxide + water → glucose + oxygen

The cells of producers contain **chloroplasts**, the organelles that carry out photosynthesis.

KEY TERMS

Photosynthesis (photosynthetic): the process of using light energy to synthesis glucose from carbon dioxide and water protoctists

Diatom: group of unicellular algae found in phytoplankton, characterised by silica skeletons

Dinoflagellate: group of unicellular algae found in phytoplankton, characterised by the presence of two flagella

Cyanobacteria: group of photosynthetic bacteria found in marine and fresh water

Enzyme: a protein produced by a living organism that acts as a catalyst in a specific reaction

Chloroplast: the photosynthetic cell organelle found in eukaryotes

Endosymbiosis: a theory that suggests that chloroplasts were originally independent photosynthetic bacteria that were taken in by other cells

Chloroplasts

Different types of chloroplast are found in different species of producers, although they all have some common features. The structure of chloroplasts provides clues about their origins, which is thought to involve a process called **endosymbiosis**. All chloroplasts contain their own DNA and ribosomes, and show structural similarities to a group of photosynthetic bacteria called cyanobacteria. It is thought that, at some point, cyanobacteria were engulfed by other cells but were not broken down, so were able to live within these cells. Eventually, the cyanobacteria lost their independence and became chloroplasts.

The majority of green algae and plants have chloroplasts similar to the general structure shown in Figure 8.1.

KEY TERMS

Thylakoid: a flattened, membrane-bound, fluid-filled sac that is the site of the light-dependent reactions of photosynthesis in a chloroplast granum

Stroma: the fluid part of a chloroplast in which the carbohydrates are synthesised

Ribosome: cell organelle involved in protein synthesis

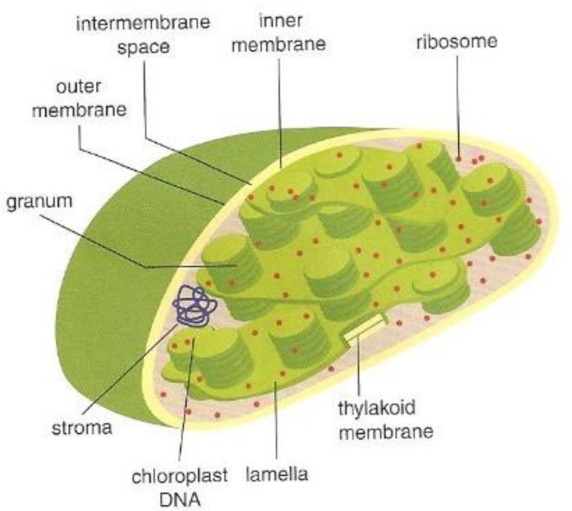


Figure 8.1. Diagram of a chloroplast found in typical green plants and algae.

Chloroplasts are covered with two membranes, one of which is probably a legacy of the original bacterial ancestor and the other a legacy of the ancestral host cell. Inside the chloroplast is an extensive network of membranes called **thylakoids**. These have stacked areas called grana, which contain the photosynthetic pigments. The thylakoid membranes are where light energy is trapped, and the extensive network ensures that a large surface area is exposed to the light. Surrounding the thylakoid membranes is a fluid called the **stroma**. This contains many chemicals and enzymes and is where glucose and other sugars are synthesised. The stroma also contains **ribosomes**, DNA and other substances, such as insoluble starch granules and lipid droplets.

KEY TERMS

Primary pigment: photosynthetic pigment that is directly involved with photosynthesis

Chlorophyll (*a* and *b*): green pigments responsible for light capture in photosynthesis in algae and plants

Accessory pigment: a pigment that is not essential for photosynthesis but that absorbs light of different wavelengths and passes the energy to chlorophyll si such as chlorophyll *b*, carotenoids and xanthophylls

Carotenoid: a yellow, orange or red plant pigment used as an accessory pigment in photosynthesis

Xanthophyll: a yellow or brown plant pigment used as an accessory pigment in photosynthesis

The primary and accessory pigments found in producers

The thylakoid membranes contain a range of different pigments that absorb light. The **primary pigment** that is most important in photosynthesis is **chlorophyll *a***, but there are many other **accessory pigments**, including **chlorophyll *b***, the **carotenoids** and **xanthophylls**. The chlorophylls give most plants their green colour. Different species of producer often have different accessory pigments depending on their particular habitats, and this will be discussed later in this chapter.

You can separate and identify different pigments by carrying out paper chromatography. In chromatography, the pigments are extracted from the producers and dissolved in a solvent. The extract is then placed on a strip of chromatography paper and the wick of this placed into more solvent. As the solvent moves up the paper, the pigments dissolve and are carried up the paper. Pigments that are more soluble travel faster and so run further up the paper, as shown in Figure 8.2.

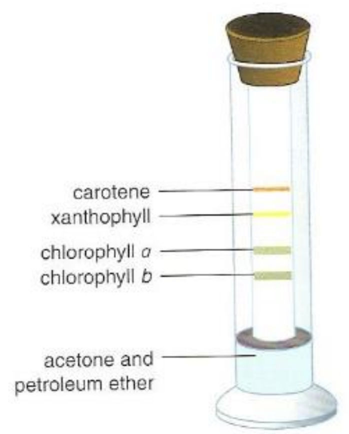


Figure 8.2. Separation of photosynthetic pigments by chromatography.

pigment	colour	R_f value
chlorophyll *a*	green	0.45
chlorophyll *b*	blue/green	0.65
xanthophyll	yellow/brown	0.71
phaeophytin	grey	0.83
carotene	yellow	0.95

Table 8.1. R_f values for different pigments in propanone solvent.

Conclusions

Use Table 8.1 to identify each pigment on your chromatograph.

Absorption and action spectra

Different colours of light have different wavelengths. The different pigments found in producers absorb light wavelengths of slightly different colours. The **absorption spectrum** of a pigment shows the amount of light of each wavelength that a particular pigment absorbs. The absorption spectra of chlorophylls *a* and *b* and carotene are shown in Figure 8.4. The graph shows clearly the two peak areas of absorption of both chlorophylls around the blue and red ends of the spectrum. Most plants are green in colour because they reflect or transmit green light but absorb light in the red and blue areas of the spectrum. The overall absorption spectrum of a particular producer will be the combined absorption spectra of all its pigments.

An **action spectrum** shows the actual effect of different light wavelengths on the rate of photosynthesis. It can be obtained by measuring the rate of photosynthesis of a producer at different light intensities. The shapes of action and absorption spectra are usually the same. This means that the light wavelengths used in photosynthesis are the same ones that are absorbed (Figure 8.5). Details of a simple practical for seeing this are given later.

KEY TERMS

Absorption spectrum: a graph of the absorbance of different wavelengths of light by a compound such as a photosynthetic pigment

Action spectrum: a graph showing the effect of different wavelengths of light on a process, for example on the rate of photosynthesis

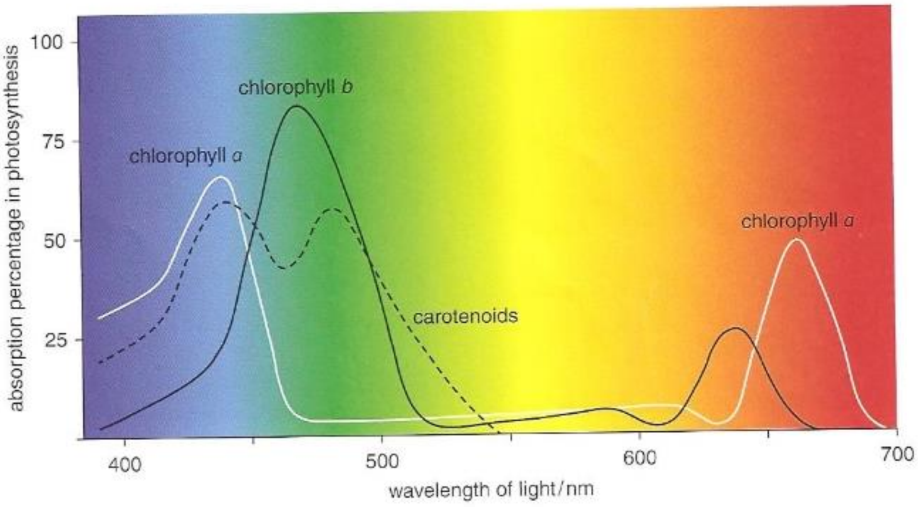


Figure 8.4. Absorption spectra of chlorophyll *a*, chlorophyll *b* and carotenoids.

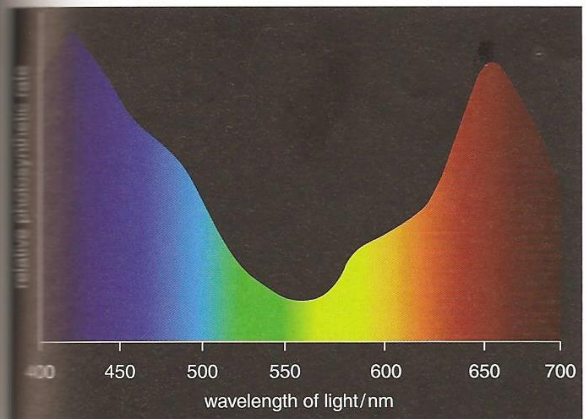


Figure 8.5. Photosynthetic action spectrum for a typical producer.

The pigments present in different species of marine primary producers are linked to the depth of water that they inhabit. Different light wavelengths penetrate to different depths in the water, so the wavelengths of light available to a particular producer depend on the depth it inhabits.

SELF-ASSESSMENT QUESTIONS

1 Explain what is meant by the terms absorption spectrum and action spectrum.

2 In 1882, Theodor Engelmann carried out an experiment to investigate the effect of light wavelength on the rate of photosynthesis of the filamentous alga, *Spirogyra*. He placed a filament of the alga on a microscope slide with some aerobic bacteria that moved towards areas of higher oxygen concentration. He used a prism to illuminate the algal filament with different wavelengths of light and then observed the movement of the bacteria.

   a Suggest why aerobic bacteria that move towards oxygen were used.

   b State what the production of oxygen by the chloroplasts shows.

   c Explain the results shown in Figure 8.6.

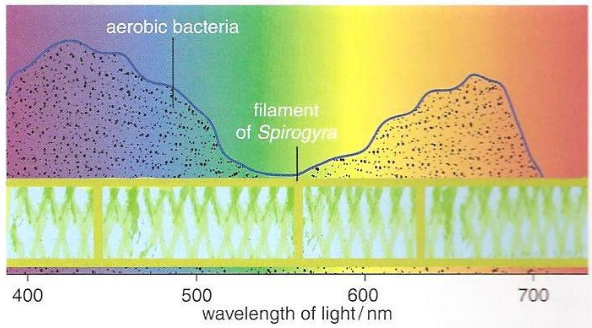


Figure 8.6. Results from Englemann's experiment showing which parts of the algal filament the aerobic bacteria have migrated towards.

Light penetration in water: wavelength and turbidity

There are two main factors that affect how deep in the water light can penetrate:

- the wavelength, or colour, of light
- the amount of particulate material, known as turbidity, in the water.

Light wavelength

Figure 8.7 shows the maximum depths to which different wavelengths of light penetrate. It also demonstrates that all wavelengths of light penetrate further in less turbid, open ocean waters than coastal waters.

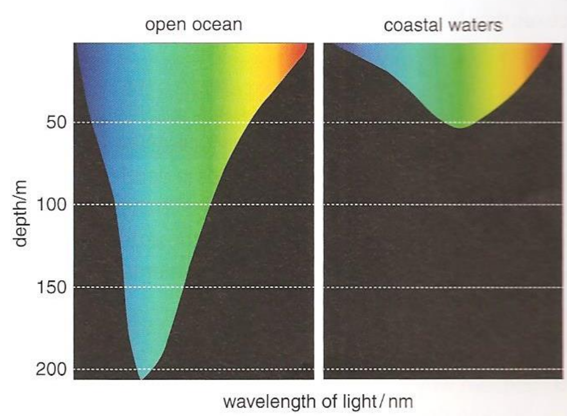


Figure 8.7. Penetration of different light wavelengths in clear ocean waters and turbid coastal waters.

Blue light reaches the deepest parts of the ocean, up to a maximum depth of about 200 m, while red light penetrates the least and is absorbed by the surface water within the first 10 m. Any producers living below 10 m only receive light from the blue and green areas of the spectrum. Chlorophylls *a* and *b* and carotene absorb very little light from the green area of the spectrum, which creates a potential problem. Red and brown algae are adapted to live in these depths, possessing accessory pigments such as xanthophyll and a group of pigments called phycobilins. Phycobilins are pigments that are bound to proteins, forming protein–pigment complexes called phycobiliproteins. There are several different phycobiliproteins, the main two being phycoerythrin and phycocyanin; their absorption spectra are shown in Figure 8.8.

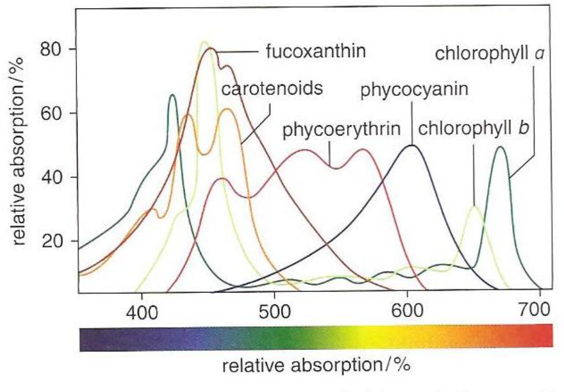


Figure 8.8. Absorption spectra of chlorophylls *a* and *b*, fucoxanthin (a xanthophyll found in algae), carotenoids, phycoerythrin and phycocyanin.

These accessory pigments enable red and brown algae to absorb light from the yellow and green areas of the spectrum. This increases their rate of photosynthesis in depths where there is no red light. Red and brown algae with these pigments are able to compete and survive better at these depths than green algae, which lack these accessory pigments.

SELF-ASSESSMENT QUESTIONS

3 Explain why a diver's red oxygen tank appears black in deeper water.

4 It has been suggested that it is energetically very costly to produce phycoerythrin and phycocyanin. Suggest why algae found at the surface do not contain these pigments.

Turbidity

Large amounts of sediment, particles or even living organisms such as plankton, reduce light penetration. The cloudiness or clarity of the water is known as **turbidity**. Estuarine and coastal water generally has a greater turbidity than open ocean water so light is less able to penetrate to lower depths (Figure 8.7). Light penetration can easily be measured by using a piece of apparatus known as a Secchi disc. This is a white 30 cm circular metal or plastic disc attached to a rope. The disc is lowered into the water until it is no longer visible and the length of rope recorded. The disc is then raised and the length of rope when the disc becomes visible measured (Figure 8.9). An average distance is then calculated using the two values.

KEY TERM

Turbidity: the cloudiness of water or other fluids due to the presence of particles. It affects the penetration of light

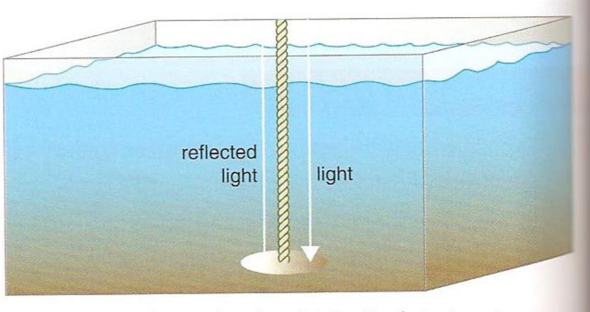


Figure 8.9. Use of a marine Secchi disc to detect water turbidity.

In areas of ocean with high turbidity and low light penetration, producers are less able to live at lower depths because they are unable to photosynthesise.

SELF-ASSESSMENT QUESTIONS

5 Explain why coastal waters have lower light penetration than open ocean.

6 Suggest why an average distance is calculated for visibility of the Secchi disc rather than relying on the distance it immediately becomes no longer visible.

Diatoms

Diatoms are unicellular phytoplankton found in the oceanic surface water. There are over a hundred different genera but all have intricate cell walls of silica, which often have extraordinarily beautiful designs (Figure 8.15). They are able to reproduce very rapidly when conditions are optimal and blooms are often seen in spring. This is when light intensity and temperature are rising and upwelling of mineral ions into the surface waters occurs. The blooms tend to appear and then rapidly disappear because of consumption by primary consumers such as planktonic crustaceans and krill, and depletion of mineral ions. They are very important in removing carbon dioxide from the atmosphere and form the base of many marine food webs.

Figure 8.15. Diatoms come in a range of sizes and shapes, many of which show extraordinary geometric patterns.

Dinoflagellates

Dinoflagellates are also unicellular protoctists but do not have the silica cell wall that diatoms possess. Like diatoms, they live in the upper surface waters of oceans and can undergo rapid reproduction to produce algal blooms when conditions are optimal. The blooms of some species of dinoflagellate produce toxins that can poison fish and accumulate in shellfish. Contaminated shellfish that are eaten by other organisms, including humans, can cause poisoning. Blooms of dinoflagellates that produce toxins are called harmful algal blooms (HABs) and include red tides, which cause areas of the ocean to turn red. Pollution caused by the run-off of fertiliser from fields is the source of many blooms of dinoflagellates, and as farming has become more intense the number of harmful algal blooms has increased.

Some dinoflagellates bioluminesce, and this can often be seen at night on the ocean or at the coast, when impressive displays can occur in the evening (Figure 8.16). They bioluminesce as a defence mechanism since it tends to attract large predators into the area which then consume predators of the dinoflagellates.

Figure 8.16. Blooms of dinoflagellates often light up coastal waters with their bioluminescence.

Cyanobacteria

Cyanobacteria are photosynthetic bacteria that are one of the earliest known forms of life on Earth. They are found almost everywhere on the planet and are considered to be one of the most successful bacteria. When cyanobacteria evolved, their photosynthetic activity caused a huge increase in the oxygen levels of the planet's atmosphere, which allowed aerobic life to evolve. Planktonic cyanobacteria are filamentous organisms that are found in surface waters (Figure 8.17). Like dinoflagellates and diatoms, they undergo rapid reproduction if the conditions are optimal, producing blooms. Some species produce very harmful cyanotoxins such as BMAA, an altered amino acid, which is now thought to be a possible environmental cause of neurological diseases in humans, such as Alzheimer's and Parkinson's. The blooms are often associated with high levels of pollution from fertilisers and organic waste.

Sargassum

Sargassum is a genus of brown macroalgae (seaweed) in the order Fucales. A piece of *Sargassum* is shown in Figure 8.18. Numerous species are distributed throughout the temperate and tropical oceans of the world, where

Figure 8.17. Cyanobacteria seen with a light microscope clearly show their filamentous structure.

they generally inhabit shallow water and coral reefs, and the genus is widely known for its planktonic (free-floating) species. Many species that are usually attached to a substrate may also survive as free-floating forms after being detached from reefs during rough weather. Two species (*S. natans* and *S. fluitans*) have become holopelagic: they reproduce vegetatively and never attach to the seabed during their life cycle.

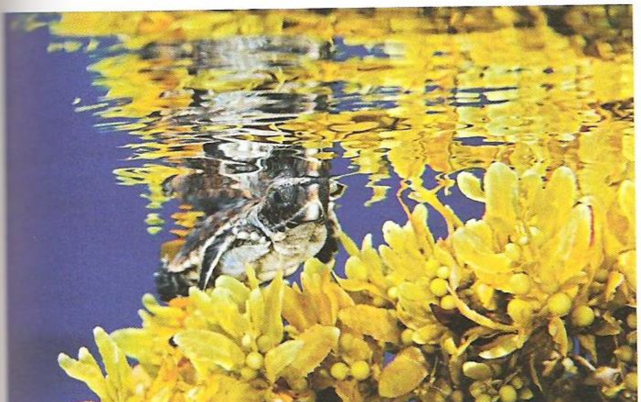


Figure 8.18. A mat of oceanic *Sargassum natans* clearly showing the spherical air bladders used for floatation. Note the turtle swimming between the *Sargassum* and the water surface.

Sargassum was named by the Portuguese sailors who found it in the Atlantic Ocean after a species of rock rose called sargaço that grew in their water wells at home. In turn, the Atlantic Ocean's Sargasso Sea is named after the algae, because it contains large amounts of *Sargassum*. It is thought that the free-floating *S. natans* grows during the spring in the north-west Gulf of Mexico and is then transported into the Atlantic by strong currents. Although it was formerly thought to cover all of the Sargasso Sea, making navigation impossible, it has since been found to occur only in drifts. The Florida Keys and its smaller islands are well known for their high levels of *Sargassum*, which often covers their shores and beaches.

The free-floating forms of *Sargassum* found in the open ocean usually form long floating mats. They have no roots, are composed of very tough, flexible fibres that can resist pounding by the ocean waves, and have air bladders called pneumatocysts that help them stay afloat. These free-floating species provide a food source and serve as a shelter for a rich diversity of marine life, including turtles, puffer fish, crustaceans and the camouflaged Sargassum fish.

Shallow water

In clear coastal waters, light often penetrates to the seabed so producers are able to attach to a substrate and still photosynthesise. They are fixed to the seabed to prevent being washed away by waves and ocean currents. There are several different species that all possess certain adaptations to enable them to survive in this environment. As you have seen earlier in this chapter, as water depth increases, different light wavelengths 'disappear' as they are absorbed by the water. Producers growing in shallow waters have different combinations of pigments depending on the depth of water they live in. Many that live below certain depths have little exposure to red light wavelengths.

KEY TERM

Mutualism: a relationship between two different organisms where both organisms benefit

Zooxanthellae

Zooxanthellae are dinoflagellate protoctistans that are found growing inside other marine organisms. They are found within coral polyps, giant clams, jellyfish and sea anemones. They enter into the cells of their host by a process of endocytosis, or are transferred from parents during reproduction, and remain there in a **mutualistic** relationship. The dinoflagellates photosynthesise and release glucose and amino acids into the coral cells and the coral provides the dinoflagellates with carbon dioxide and minerals. Figure 8.19 shows coral polyps containing zooxanthellae. Many of the host organisms live where there is no red light, so the zooxanthellae contain accessory pigments (for example peridinin and diadinoxanthin) as well as chlorophylls. This means that they are able to maximise the absorption of additional wavelengths of light. These pigments often give corals their red and yellow colours.

Zooxanthellae may also be found as free-living dinoflagellates that are taken up by coral polyps. During the life of a coral, zooxanthellae may be expelled when the coral becomes stressed. This expulsion of the zooxanthellae is known as coral bleaching and can be caused by global warming and pollution. After a coral has undergone bleaching, it may be recolonised by a different species of zooxanthellae. This means that, within its lifetime, an individual coral may be colonised by several species of zooxanthellae, changing colour several times.

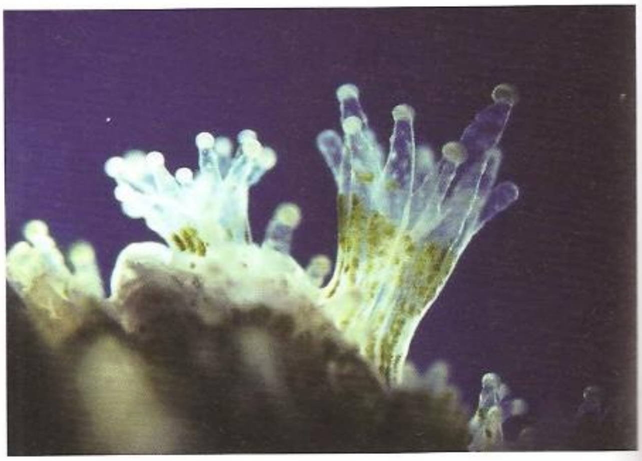


Figure 8.19. Coral polyps showing yellow-brown zooxanthellae within them.

Seagrasses

Figure 8.20. Submerged seagrass growing on the seabed.

Seagrasses (Figure 8.20) are not to be confused with seaweeds. They are green, flowering plants that grow on the seabed in shallow waters and look like underwater meadows. There are about 60 different species of seagrass, all of which are restricted to the photic zone and photosynthesise very much like terrestrial flowering plants. They play many important roles in coastal areas, acting as oxygen producers and primary producers for food webs. They are the main food source for organisms such as turtles, manatees and herbivorous fish. They also provide a habitat and nursery for many species of fish and crustaceans, some of which are commercially valuable fishery species. Their root systems stabilise the substrate and prevent coastal erosion and wave damage. It is estimated that seagrass meadows account for more than 10% of the ocean's total carbon storage and, because of their high productivity, they hold twice as much carbon dioxide per hectare as rainforests. Seagrasses are one of many species thought to be under threat from global warming. Seagrasses have many specific adaptations.

- They have well-developed root systems, with thick, horizontal rhizomes that lie up to 25 cm deep in the substrate (Figure 8.21). The root system anchors the seagrass into the seabed so that it is not moved by the shifting water currents and wave actions. The rhizomes also enable seagrasses to reproduce asexually.

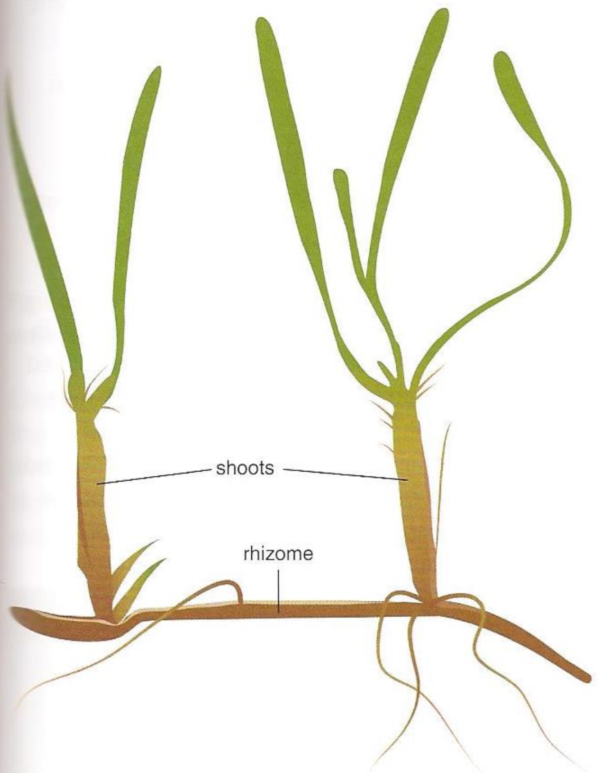


Figure 8.21. Seagrass showing the thick rhizome and two separate shoots.

- They are physiologically adapted to seawater so that their cells are able to exist in salt water without losing water by osmosis.
- They contain a specialised tissue within stems called aerenchyma. This tissue contains air and delivers it to all the submerged areas of the plant.
- The leaf structure is unusual. It has an epidermis layer with chloroplasts (these are absent in the epidermis of most terrestrial plants) to maximise photosynthesis, no stomata, and a very thin waxy cuticle so that the leaf cells can obtain mineral ions directly from the water. Seagrasses have very few vascular bundles, as there is no need to transport water or minerals through the plant. The leaves are also very flexible so they do not get broken by water currents.
- They are able to reproduce both sexually and asexually. When reproducing sexually, they produce flowers that release pollen that is carried in the water to other flowers.

One species of seagrass that is particularly well known is *Thalassia testudinum,* often called turtle grass. It is found in the Gulf of Mexico, Caribbean Sea and Bermuda, and plays an important role in these areas' ecosystems. It is a vital food source for many rare, endangered species, including turtles.

Kelp forests

Figure 8.22. Giant kelp forests.

Kelp species (Figure 8.22) are giant brown macroalgae that often grow as underwater forests. They require nutrient-rich water and a temperature of between 8 and 16°C. When conditions are optimal, they have a very high rate of growth. One genus, *Macrocystus*, is able to grow up to 0.5 metres a day and can reach lengths up to 80 m. Kelp forests are often considered to be underwater rainforests because they are the base of many food webs generating vast species biodiversity. They also stabilise and create a habitat and shelter for many species of animal, including commercially important fish. Sea urchins are one of the species that eat kelp. Sea otters prey on sea urchins, and where sea otter populations have decreased, kelp forests have also decreased because of a dramatic increase in the sea urchin population. The loss of kelp has then led to a fall in reported fish catches.

Most kelp species have a similar structure that enables them to survive in the water of shallow seas and oceans (Figure 8.23).

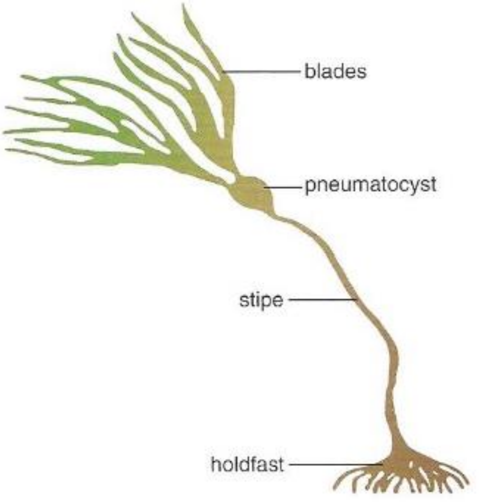


Figure 8.23. The basic structure of kelp, showing the holdfast, stipe, pneumatocyst and blades.

The whole body of the kelp is known as a thallus and has three main parts.

- Holdfast: this is a strong, root-like structure that anchors the kelp to the seabed, preventing it from being moved by strong ocean currents or storms. It is for anchorage only and has no function in absorbing minerals.
- Stipe: this is a long, tough, vertical stalk similar to the stem of plants. It extends from the holdfast and reaches up to the blades. It is very tough, to prevent breakage.
- Blades: the blades are broad leaf-like structures that 'hang' in the water. They have a large surface area to absorb light and minerals.

Some kelp species also have structures called **pneumatocysts**, which are gas-filled bladders found underneath the blades. These act as floatation aids to keep the kelp upright.

Because many kelp species live at depths where exposure to red light is restricted, they contain accessory pigments such as xanthophyll and fucoxanthin to absorb additional wavelengths of light.

KEY TERM

Pneumatocyst: a gas-containing structure that provides buoyancy for some species of seaweed area. **Net primary production** (NPP) is the amount left over to create new biomass after respiration (R) has been taken into account. This can be shown by the following equation:

NPP = GPP – R

It is this net primary production that is available to pass on to the consumers. **Secondary production** is the amount of biomass produced by heterotrophs after eating the producers. Hence the more productive an ecosystem, the more energy is available to pass along the food chain. In the marine environment, there is no large-scale accumulation of biomass as there is in savannahs and forests on land. However, the reproductive rate of the phytoplankton is very high so there is a constant source of new organisms to photosynthesise. Carbon dioxide from the atmosphere dissolves in the water and is then available for photosynthesis. When it is fixed into glucose it is stored as phytoplankton biomass. Much of this 'locked up' carbon dioxide sinks to the floor of the ocean when organisms die. This process is discussed in detail in Chapter 4.

KEY TERMS

Gross primary production: the amount of light or chemical energy fixed by producers in a given length of time in a given area

Net primary production: the amount of energy that is left over after respiration to be made into new plant biomass

Secondary production: the rate of production of new biomass by consumers, using the energy gained by eating producers

Measuring productivity

There are several ways in which primary productivity can be estimated:

- using the rate of photosynthesis of producers
- using the rate of increase in the biomass of producers
- looking at the amount of chlorophyll in an ecosystem.

For example, the higher the rate of growth of producers, the higher the amount of chlorophyll present. Net primary production and gross primary production are usually given as units of energy per unit area per unit of time, for example kJ m^{-2} $year^{-1}$. However, the units used vary depending on the method of measurement chosen.

Rate of photosynthesis

The rate of photosynthesis can be found by looking at the change in either the oxygen or carbon dioxide concentrations. If photosynthesis is taking place, there will be a decrease in the concentration of carbon dioxide and an increase in the concentration of oxygen.

Because the majority of marine producers are single-celled phytoplankton, they are easy to keep in a closed system such as a bottle. If a bottle is placed in the light, both photosynthesis and respiration will take place. If a bottle is in the dark, there will be no photosynthesis but respiration will continue. If you assume that the rate of respiration remains relatively constant, you can compare the readings of bottles kept in the dark and light to work out the rate of photosynthesis (Figure 3.5). The levels of oxygen in the water can be measured with a dissolved oxygen sensor. You need to take three readings:

- the initial reading before the experiment begins
- the reading in the light bottle at the end of the experiment
- the reading in the dark bottle at the end of the experiment.

The results would be tabulated as shown in Table 3.3.

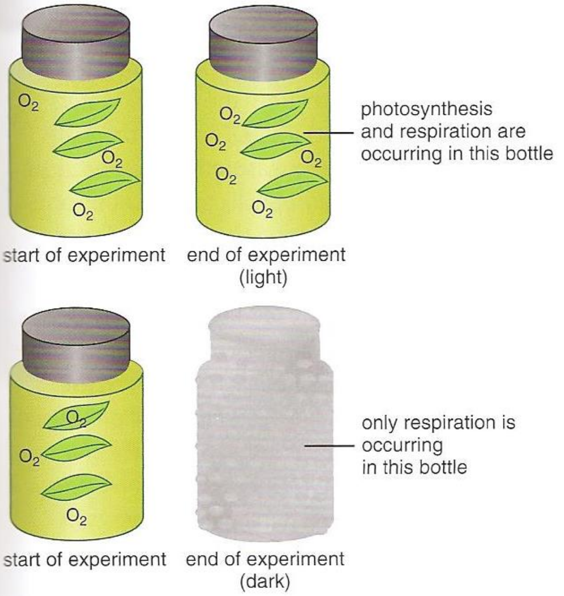


Figure 3.5. The light- and dark-bottle method for measuring productivity. The LH bottles represent start of experiment and RH bottles represent end of experiment.

bottle	amount of oxygen / mg dm^{-3} h^{-1}
start of experiment	6
end of experiment in the light	16
end of experiment in the dark	1

Table 3.3. A sample set of results from the light- and dark-bottle method.

The amount of oxygen in the light bottle increases because the rate of photosynthesis is higher than the rate of respiration. In the dark bottle, the only process taking place is respiration so the amount of oxygen in this bottle decreases.

The net primary production is therefore the difference between the oxygen in the bottle at the start and the oxygen in the light bottle at the end. The respiration is the difference between the oxygen at the start and the oxygen in the dark bottle at the end. The gross primary production is the difference between the light and the dark bottles at the end of the experiment.

In this example:

NPP = 16 – 6 = 10 mg O_2 dm^{-3} h^{-1}

Respiration = 6 – 1 = 5 mg O_2 dm^{-3} h^{-1}

GPP = 16 – 1 = 15 mg O_2 dm^{-3} h^{-1}

This technique can be extended to investigate the effect of light on productivity. Samples are removed from different depths in the water and placed into pairs of light and dark bottles. The bottles are then suspended at the same depth the samples were removed from. The calculations are carried out as described to work out the net primary production, gross primary production and respiration at each depth.

The productivity generally increases as you move down towards the deep chlorophyll maximum, and then decreases as the amount of light begins to limit the rate of photosynthesis (Figure 3.6). At the point where the rates of respiration and photosynthesis are equal, there is no change in the amounts of carbon dioxide or oxygen and the net productivity is zero. The light intensity at this depth is known as the **compensation point**. Below this depth, there is still light available but producers are unable to survive because the rate of respiration would be greater than the rate of photosynthesis. This part of the photic zone is sometimes called the disphotic zone. Around 90% of marine life is therefore found above the depth of the compensation point. This upper area, with sufficient light for photosynthesis is called the euphotic zone.

KEY TERM

Compensation point: the light intensity at which the rate of photosynthesis and the rate of respiration are equal

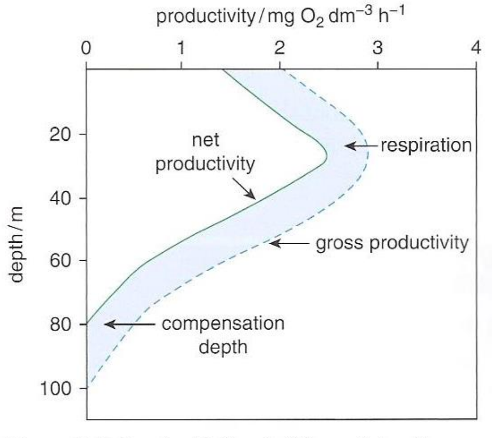


Figure 3.6. Productivity at different depths as measured by the light- and dark-bottle method.

Changes in biomass

A second way to measure productivity is to look at the rate of accumulation of biomass. This can be achieved by harvesting producers after a set amount of time, drying them to remove variations in the water content, and then finding the mass. If you know the size of the area the producers came from, you can then work out the biomass per unit area per year to give an estimate of the net primary production. As the producers would have been respiring while growing, you are unable to measure the gross primary production. There are difficulties with this method however, as you cannot measure the biomass that has already been consumed by heterotrophic organisms. This may also be true for the light- and dark-bottle method if small heterotrophic organisms are not sieved out before the experiment begins.

Satellite imagery

The other main way in which scientists monitor the productivity of the oceans is by using satellite imagery to measure the colour of the surface layers of water. This can be used to follow the changes in chlorophyll concentration and therefore the amount of producers present (Figure 3.7).

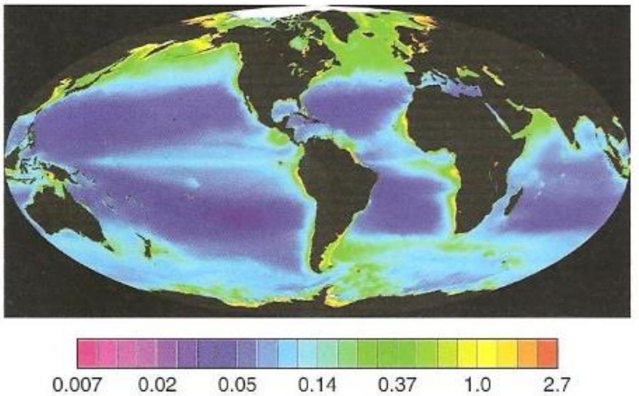


Figure 3.7. False-colour picture showing annual mean amount of chlorophyll *a* in the oceans (NASA *aqua modis*).

From Figure 3.7 you can see that the most productive areas are in the tropics and at the higher latitudes, which are shown in green and orange. The least productive areas, shown in pink and blue, tend to be where there is a smaller supply of nutrients from the deeper waters, perhaps because of wind patterns. Of course, there are problems with this method of measurement too because the relationship between chlorophyll concentration and biomass is not fixed. It depends on the individual species present and their adaptations.

The satellites can indicate only relatively shallow depths and certainly cannot penetrate the entire euphotic zone where production is taking place. However, the satellite images give a very useful summary of differences in productivity and enable scientists to monitor any changes. Recently, researchers at Sheffield University discovered that water from melting giant icebergs in the Southern Ocean contains nutrients that increase the growth of the local phytoplankton. These giant icebergs are more than 18 km in length. Scientists studied the satellite images and found that the increased productivity caused by these icebergs lasts for at least a month after they pass through an area and extend for hundreds of kilometres.

SELF-ASSESSMENT QUESTIONS

5 Explain the difference between gross primary production and net primary production.

6 a If the GPP = 53 kJ m^{-2} $year^{-1}$ and the NPP = 31 kJ m^{-2} $year^{-1}$ calculate the amount of energy used in respiration.

b Explain why organisms need to respire.

The influence of changes in productivity on the food chain

The higher the productivity, the more biomass accumulated by the producers and therefore the more biomass available for the consumers to eat. This means that, in general, higher productivities lead to more abundant populations of consumers, or longer food chains. The most productive areas of the oceans tend to be those areas with high levels of nutrients from upwelling. In tropical areas, there are high levels of light but it is also warm, which leads to a strong thermocline and little mixing of nutrients from deeper waters. In contrast, polar waters are nutrient rich because it is very cold and there is therefore only a weak thermocline. However, productivity is only high in the summer when the light levels are higher.

There does come a point when productivity can be too high. This leads to effects that are similar to the process of eutrophication seen in fresh-water ecosystems. If the levels of nutrients increase too much or too rapidly, phytoplankton may rapidly increase in a phenomenon known as an **algal bloom**.

In these circumstances, up to 5 million cells per litre can be produced, which is very damaging to the ecosystem. This density of algae is so high that it can clog the gills of fish so that they are unable to obtain enough oxygen. Once the algal cells die they are broken down by decomposers such as bacteria so there is also an increase in bacterial populations. The bacteria respire and grow and use up the oxygen in the water, which can lead to **hypoxic** conditions (lacking oxygen). This also kills heterotrophic organisms because without oxygen they cannot respire.

If the algal species involved also produce toxins, the effects can be even worse because the organisms that ingest them will be poisoned. This can cause mass mortality in aquatic organisms such as dolphins, manatees and whales, as well as food poisoning in people who eat contaminated shellfish. You can read more about these harmful algal blooms in Chapter 8.

KEY TERMS

Algal bloom: a rapid increase in a population of algae

Hypoxic: an area of water with a low concentration of dissolved oxygen

SELF-ASSESSMENT QUESTIONS

7 **a** Evaluate the use of different methods to measure ocean productivity.

b Explain why giant icebergs increase productivity of the oceans.

8 **a** Explain why it can be damaging for nutrient levels in water to increase too much.

b Suggest why waters at high latitudes normally have higher productivity than tropical waters.

3.3 Energy transfer

Only a small amount of the radiation from the Sun is fixed by the Earth's producers. Some of the radiation never reaches the producers because it is reflected back into space. Of the light that does reach the ocean, some is absorbed, reflected or scattered by the water.

The remainder is available to the producers but even then it cannot all be used. Some is the wrong wavelength for the pigments of producers to absorb. Chlorophyll, for example, absorbs red and blue light but reflects green light (which is why it appears to be green). Of the light that is the correct wavelength, some will miss the chloroplasts and still not be absorbed (Figure 3.10).

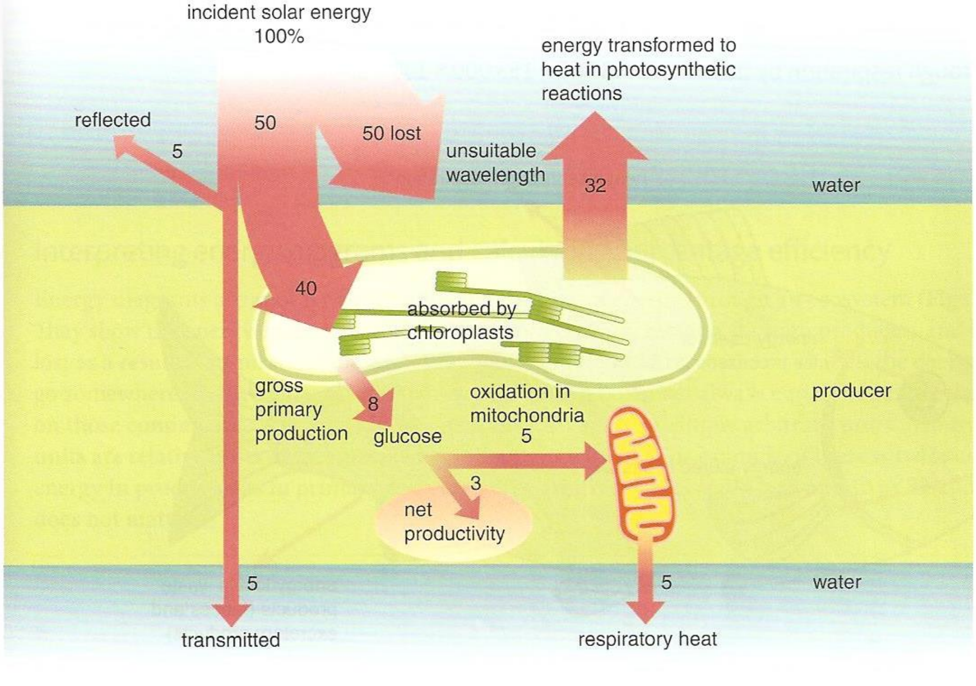


Figure 3.10. The fate of light energy falling on producers in the ocean.

The process of photosynthesis itself is not completely energy efficient. During the various chemical reactions that must take place, energy is lost as heat. Worldwide it has been estimated that producers such as green plants and phytoplankton fix about 0.06% of the total energy radiating from the Sun. But this figure can be as high as 1% in aquatic ecosystems and 2–3% on land.

Producers need some of the carbohydrates they produce for respiration. This means that only the net production of biomass is available to the next trophic level. The energy stored in biomass is passed to heterotrophic organisms when they ingest, digest and absorb the nutrients from the producers. These nutrients can then be assimilated into new biomass. If the producers are phytoplankton, then the entire cell is usually ingested by the primary consumers, passing on all the available energy. However, in the case of macroalgae and rooted plants like seagrass, there are parts of the producer that are not eaten (the roots, for example). The energy stored in these areas is therefore not available to the next trophic level, although it may later re-enter the ecosystem through decomposition when the plant dies.

Secondary production is the production of new biomass by the consumers. It can involve animals eating the phytoplankton, macroalgae and seagrass, or animals eating other animals. Decomposers such as bacteria and fungi break down dead organic matter to obtain the nutrients they need. This also releases nutrients back into the ecosystem (see Chapter 4). Secondary production depends on:

- the biomass available in the producers
- the amount of energy lost through respiration by the consumers
- the amount of energy lost in waste products such as urine (Figure 3.11).

Most salt-water fish only lose small amounts of urine and excrete most of their nitrogenous waste through their gills in the form of ammonia. Undigested food is egested as faeces.

These energy transfers can also be expressed as a formula: $C = P + R + F + U$

Where C is the energy consumed, R is the energy used in respiration, F is the energy in faeces, U is the energy in urine and other excreted waste products of metabolism, and P is the energy left over for the production of new biomass by the animal.

The energy of production (P) is then available to pass on to the next trophic level.

The efficiency of energy transfer

The efficiency of the energy transfer can be expressed as a percentage. This can be shown as:

$$\frac{\text{energy transferred to new trophic level}}{\text{energy in previous trophic level}} \times 100$$

For example, if the energy radiating from the Sun is 1 600 000 kJ m^{-2} year^{-1} and phytoplankton captures 153 000 kJ m^{-2} year^{-1} in photosynthesis, the efficiency is:

153 000 ÷ 1 600 000 × 100 = 9.6%

If 12 856 kJ m^{-2} year^{-1} is then passed to the zooplankton that make up the next trophic level, the efficiency is:

12 856 ÷ 153 000 × 100 = 8.4%

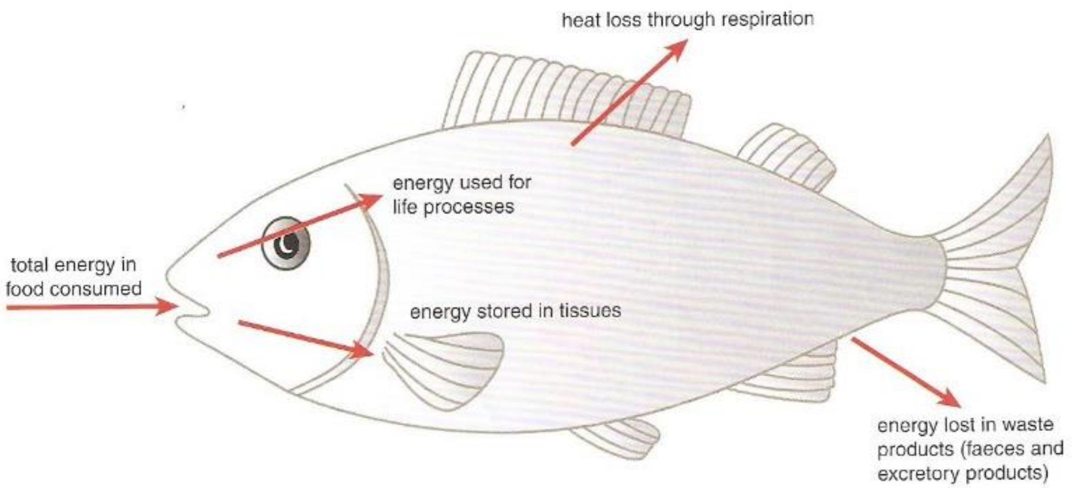


Figure 3.11. Energy transfer into and out of a consumer.

Typically the efficiency of transfer between trophic levels is around 10%, but it varies depending on:

- how much of the food is eaten
- how easy it is for the consumer to digest and assimilate the nutrients
- how much energy is used for movement
- how much is lost in the waste products of metabolism.

Some organisms are easier to digest and assimilate than others: generally, consumers find it easier to assimilate the energy in other animals than the energy in producers. If it is easier to assimilate the energy, then more of it will be passed to the next consumer. In addition, some organisms at each trophic level escape being eaten and the energy stored in their biomass will never pass to the next level.

Most fish are **ectothermic**, which means that their body temperature varies with the environmental temperature. The ocean sunfish, for example, is a secondary consumer that eats zooplankton, tiny animals present in the water that feed on the phytoplankton. The ocean sunfish is ectothermic and does not use energy in respiration to keep its body temperature higher than that of the surrounding water.

Tuna are **endothermic**, which means that they must expend energy maintaining their body temperature. Tuna occupy two trophic levels in the same food web, as secondary consumers eating zooplankton, and as tertiary consumers eating small crustaceans that have already fed on the zooplankton.

Small sharks feed on both the sunfish and the tuna but the efficiency of energy transfer is higher from the sunfish. Assuming that the sunfish and tuna take in similar amounts of energy, the tuna use more of this in respiration to keep warm so there is less to pass to the sharks. In general, the efficiency of transfer from ectothermic organisms ranges from 5% to 15% and from endothermic organisms ranges from 1% to 5%. The efficiency of transfer between the different trophic levels determines how many levels there are in the ecosystem. The higher the efficiency of transfer, the more trophic levels the ecosystem can support.

KEY TERMS

Ectothermic: an organism that maintains its body temperature by exchanging heat with its surroundings

Endothermic: an organism that maintains its body temperature by generating heat in metabolic processes

SELF-ASSESSMENT QUESTIONS

9 The total solar energy falling on phytoplankton is 1 000 000 kJ m^{-2} $year^{-1}$ and the efficiency of transfer to the phytoplankton is 1%.

a Calculate the GPP.

b If 30% of the GPP is used in respiration, then what is the NPP?

10 Describe the factors that determine how efficient the transfer of energy is.

3.4 Illustrating feeding relationships

You can show the relationships between the different trophic levels using pyramids of number, biomass and energy. These are like bar charts but are made up of horizontal bars arranged in a pyramid shape to show a particular food chain. They can be drawn to scale or simply sketched to give an idea of the changes as energy is transferred along the food chain. Producers are always at the bottom, followed by primary consumers, secondary consumers and tertiary consumers. Although energy is transferred to decomposers once the producers and consumers die, it is not often shown on the pyramid.

Pyramids of number

A **pyramid of numbers** simply shows the number of organisms present in each trophic level at a particular moment in time. The size of each horizontal bar is proportional to the number of organisms. In theory this should be quite simple but in practice it is actually rather difficult. It is often hard to estimate accurately the number of organisms present, and even once this has been achieved it can be difficult to show them to scale. For example, a typical oceanic food chain is:

phytoplankton → zooplankton → herring → mackerel → mahi mahi → shark

There could be millions of cells of phytoplankton and only one or two sharks. Finding a scale to show this is impossible. For this reason many pyramids of numbers are sketched rather than drawn to scale (Figure 3.14). In addition, much of the phytoplankton is consumed very quickly after it is produced. Thus if the numbers present in an ecosystem are counted after most have been eaten, the pyramid will be inverted (upside down) and it will look as though there are fewer phytoplankton than zooplankton. The number of organisms in an ecosystem will also vary depending on factors such as the time of year or the amount of fishing. This means that the pyramid can only show the numbers in each trophic level at a particular moment in time. Using pyramids of number also does not take into account the size of organisms, which can lead to odd-looking pyramids. For example, if several small parasites feed on one large fish you will see an inverted pyramid.

KEY TERM

Pyramid of numbers: a diagram that shows the number of organisms in each trophic level of a food chain

Pyramids of biomass

Instead of finding the number of each organism you could measure their total biomass. This overcomes the difficulties of having organisms of different sizes, such as the parasites in the last example. It does not, however, solve the issues caused by phytoplankton being eaten before they can be measured. It is possible that the

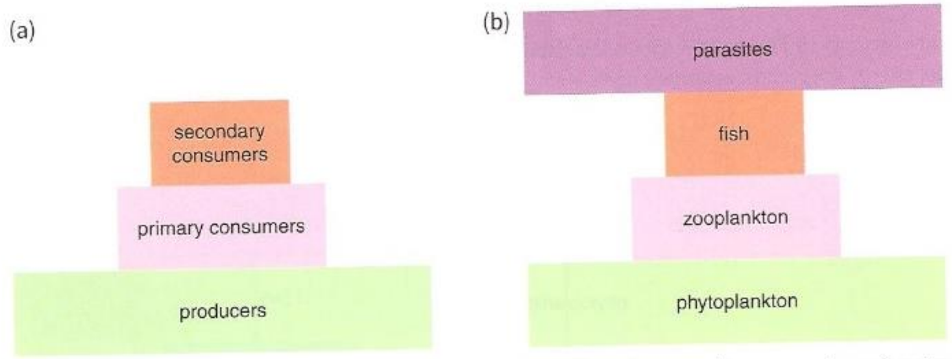


Figure 3.14. (a) A generalised pyramid of numbers; (b) A pyramid of numbers for a marine ecosystem showing small parasites feeding off a large fish.

biomass of organisms within an ecosystem could increase or decrease after measurements are taken which will make the pyramid inaccurate.

It is difficult to find the biomass of each trophic level accurately. Organisms vary in the amount of water they contain, and this water does not contribute to their biomass. For this reason dry mass should be used, with the water removed by evaporation. Clearly to do this the organisms must be killed, and it is therefore undesirable to measure the biomass of the entire food chain. Instead there are conversions available to change the mass of living material into dry mass. This still means that every individual must be found and weighed. Alternatively, the dry mass of a sample can be taken and then multiplied by the total number of organisms to give the total average dry mass. Both of these methods will give an estimate of the total biomass but neither of them will be completely accurate.

A **pyramid of biomass** may still be inverted as the total amount of biomass in phytoplankton at any one time is small because they are eaten very quickly. However, their reproductive rate is very high so they reproduce quickly enough to provide enough biomass to maintain the population of consumers. In other words the amount of biomass is low but the rate of production of biomass is high. This snapshot view of the biomass at a particular moment in time is known as the standing crop (Figure 3.15).

Pyramids of energy

A **pyramid of energy** shows the rate of production of biomass rather than the standing crop, and is therefore always pyramid shaped (Figure 3.16). It involves finding the energy in each trophic level of the food chain, which is a complex procedure. Data is collected over a long period of time, normally a year. Often conversion tables are used that will convert dry biomass into energy production. The units for pyramids of energy are kJ m^{-2} $year^{-1}$ so it will not be a standing crop but a measurement of the energy available over the entire year. Although pyramids of energy are the most difficult to produce, they are probably the most useful in terms of understanding the ecosystem.

KEY TERMS

Pyramid of biomass: a diagram that shows the biomass present in each trophic level of a food chain

Pyramid of energy: a diagram that shows the amount of energy in each trophic level of a food chain

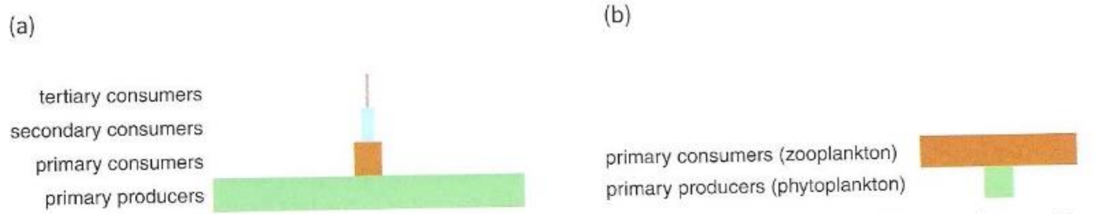


Figure 3.15. (a) Pyramid of biomass showing the decrease in biomass through the food chain; (b) Inverted pyramid of biomass showing the problems caused by the standing crop of rapidly reproducing phytoplankton.

Productivity and depth of water

There are three distinct zones in marine waters that relate to the depth of light penetration and productivity. The upper layer of water, where there is high light penetration, is called the euphotic zone. This zone may extend to about 200 m in clear water or only about 5 m in turbid water. Producers are able to photosynthesise effectively in this zone. Below the euphotic zone is the disphotic zone, often referred to as the twilight zone. This zone has some blue light but at a low intensity and ranges from between 15 m in highly turbid water to 1000 m in very clear water. No producers are found here, despite the presence of some light. Below the disphotic zone is the aphotic zone, where less than 1% of the surface light reaches. There are no producers here that use photosynthesis as a method of primary productivity. The zones are shown in Figure 8.11.

To understand why there are no producers in the disphotic zone, despite the presence of light, you need to consider the processes of photosynthesis and respiration.

If you look at the basic equations for photosynthesis and respiration, it becomes immediately obvious that they are exact opposites.

Photosynthesis: $6\,CO_2 + 6\,H_2O \rightarrow C_6H_{12}O_6 + 6\,O_2$

Respiration: $C_6H_{12}O_6 + 6\,O_2 \rightarrow 6\,CO_2 + 6\,H_2O$

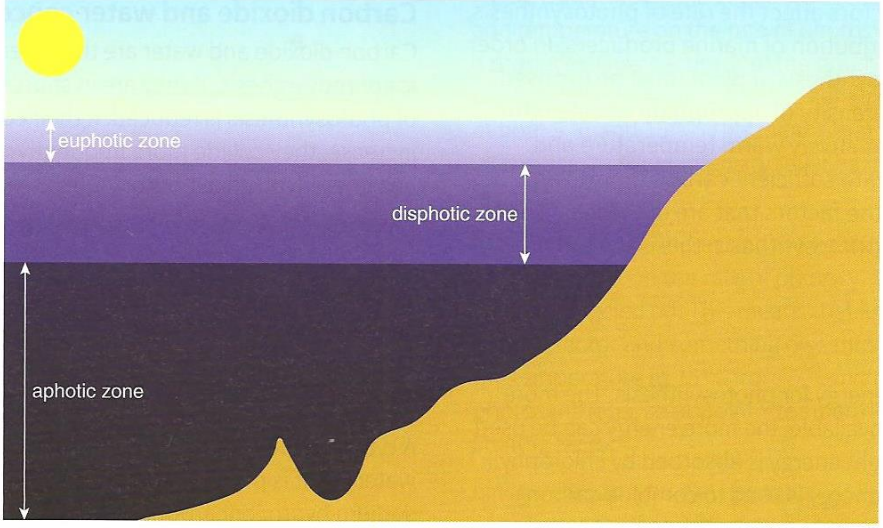


Figure 8.11. The euphotic, disphotic and aphotic zones of the ocean.

Photosynthesis builds up glucose, which has energy from light locked into it. The glucose is converted into other compounds, such as starch and protein, which are used for storage and growth. Respiration releases the energy in the glucose by oxidation.

The total amount of energy fixed by a plant into chemical compounds by photosynthesis is the **gross primary productivity** (GPP). This is not all available for growth as the plant has to use some of the glucose in respiration (R) to release energy for active processes. **Net primary productivity** (NPP) is a measure of what energy the plant is able to fix into its chemical compounds and use for growth. It is calculated using the formula:

net primary productivity (NPP)
= gross primary productivity (GPP) – respiratory loss (R)

It is clear that, if a producer is to grow, its rate of photosynthesis must exceed its rate of respiration. In the euphotic zone, the light intensity is sufficient to enable a rate of photosynthesis that is greater than the rate of respiration, so that the NPP has a positive value. In the disphotic zone, despite the producers being able to photosynthesise, the average rate is lower than that of respiration, so the NPP value is negative, resulting in the producers being unable to grow. If the rate of respiration equals the rate of photosynthesis, the producer is said to be at the compensation point and there is no net production of glucose. There may be periods during a summer day when the rate of photosynthesis exceeds the rate of respiration but over an extended period, such as a year, the mean rate of respiration is higher.

KEY TERMS

Gross primary productivity: the amount of light or chemical energy fixed by producers in a given length of time in a given area

Net primary productivity: the amount of energy that is left over after respiration to be made into new plant biomass

8.3 Factors affecting the rate of photosynthesis and the law of limiting factors

Several external factors affect the rate of photosynthesis:

- light intensity
- light wavelength
- temperature
- carbon dioxide concentration.

As these abiotic factors affect the rate of photosynthesis, they affect the distribution of marine producers. In order to maximise photosynthesis, a plant must be exposed to sufficient light intensity of appropriate wavelengths, must be kept at a relatively warm temperature and must be supplied with sufficient carbon dioxide and water. In practice, the factors that are in the least supply restrict the rate of photosynthesis: this is the law of **limiting factors**.

Light intensity

Light provides the energy for photosynthesis. The more light energy that is available, the more energy can be used to make glucose. Light energy is absorbed by chlorophyll and this harvested energy is used to combine carbon dioxide with water to make sugars. The higher the light intensity, the faster the rate of photosynthesis. This can be measured by the increasing rate of oxygen production.

Light wavelength

As you have already seen, producers contain pigments that absorb the light. Depending on the pigments present, different wavelengths of light are absorbed. Most producers are unable to absorb certain colours of light, such as green. Many contain accessory pigments, such as phycoerythrin, phycocyanin, and xanthophyll, which enable them to absorb additional light wavelengths.

Temperature

A suitable temperature is essential to maximise the rate of photosynthesis. Carbon dioxide and water molecules are combined by the action of enzymes. These molecules constantly move in random directions and react when they collide with each other. As the temperature rises, kinetic energy (the energy of movement) increases, so they move faster. Faster moving particles collide more frequently, so photosynthesis becomes faster. If the temperature rises too high, the enzymes denature, causing the reaction to slow down to almost zero.

KEY TERM

Limiting factor: the one factor, of many affecting a process, that is nearest its lowest value and hence is rate limiting. Photosynthesis rate is usually limited by light intensity, temperature and / or carbon dioxide concentration

Carbon dioxide and water concentrations

Carbon dioxide and water are the essential raw materials for photosynthesis. If they are in short supply, the rate of photosynthesis is reduced. If their concentrations increase, they collide more frequently with the enzymes involved in photosynthesis, and the rate of photosynthesis increases. In practice, water is not considered to be a limiting factor because it is rarely in short supply.

It is easy to measure the effects of these factors on photosynthesis by measuring the rate of production of oxygen by an aquatic plant such as *Cabomba*.

A typical experimental setup is shown in Figure 8.10. The water plant is placed into a boiling tube in a solution of sodium hydrogencarbonate, which provides a source of carbon dioxide for photosynthesis. The cut end of the stem is arranged below a capillary tube so that oxygen produced by photosynthesis collects in the tube. The plastic tube and capillary are also filled with sodium hydrogencarbonate. The tube containing the plant is placed into a water bath and a light source is placed next to it. The beaker of water prevents the lamp heating up the plant.

When oxygen has been collected for a set period of time, the syringe is used to draw up the bubble of oxygen and line it up against the scale so that the length of it can be measured. The limiting factors can be changed using methods shown in Table 8.3.

limiting factor	method of altering factor
light intensity	set light source at different, measured, distances from plant
light wavelength	place coloured filters in front of light source
temperature	change temperature of water bath and measure with thermometer
carbon dioxide concentration	alter concentration of sodium hydrogencarbonate solution

Table 8.3. Altering different limiting factors.

Figure 8.12 shows how you can present the effects of changing limiting factors.

Opdracht bij les 1.3

- Bekijk de diatomeeën (fytoplankton) en de larven van de noordzeekrab (zoöplankton) onder de microscoop en maak hier tekeningen van
  EN
- Kiezen uit case studies: Dode zone Golf van Mexico / Zeewier als voedsel / Mariene algenbloei en rode getijden
  OF
- Zoek een artikel over één van de autotrofe organismen die nu een plaag vormt en vat kort samen waar deze plaag door wordt veroorzaakt en wat de gevolgen hiervan zijn

Les 2.1 - De dode zone van de Golf van Mexico

De Golf van Mexico is een oceaanbasin omgeven door de Verenigde Staten, Mexico en Cuba. Het is ongeveer 1500 km breed en verbonden met de Atlantische Oceaan en de Caribische Zee.

Een dode zone is een stuk water waar zuurstofniveaus extreem laag zijn (hypoxisch). Dit betekent dat er te weinig zuurstof is voor respiratie en organismen sterven of vertrekken naar een ander gebied. Dode zones komen voor in kustgebieden waar hoge concentraties voedingsstoffen van landbouw afkomstig in de zee belanden.

Dode zones vormen wanneer voedingsstoffen zoals fosfaten en nitraten in het water terecht komen. Deze zijn vooral afkomstig van kunstmest en rioolwater. Dode zones kunnen zich ook op een natuurlijke manier vormen doordat voedingsstoffen vanaf grote diepte omhoog komen door stromingen en de wind. Deze extra voedingsstoffen zorgen voor een enorme groei van algen, die dan een algenbloei vormen. Vooral blauwgroene cyanobacteriën, die niet door zoöplankton gegeten worden, stijgen met grote getallen. Als deze organismen sterven, zinken ze naar de bodem, waar ze een voedselbron zijn voor reducenten. Deze reducenten nemen in aantal toe en hun respiratie verbruikt de meeste zuurstof. Daardoor wordt het water hypoxisch en sterven andere organismen.

De Golf van Mexico heeft een interessante dode zone. Ten eerste, het is de op een na grootste ter wereld. Ten tweede, de dode zone is seizoengebonden en de grootte varieert met de weersomstandigheden. Voedingsstoffen worden aan het water toegevoegd door de Mississippi rivier en het rioolwater van twaalf miljoen mensen. Er is veel landbouw, dus het regenwater neemt de kunstmest mee de zee in. Ongeveer 1,7 miljoen ton voedingsstoffen worden jaarlijks aan de Golf van Mexico toegevoegd. In het voorjaar en de zomer veroorzaakt dit algenbloeien en daarmee dus de dode zone.

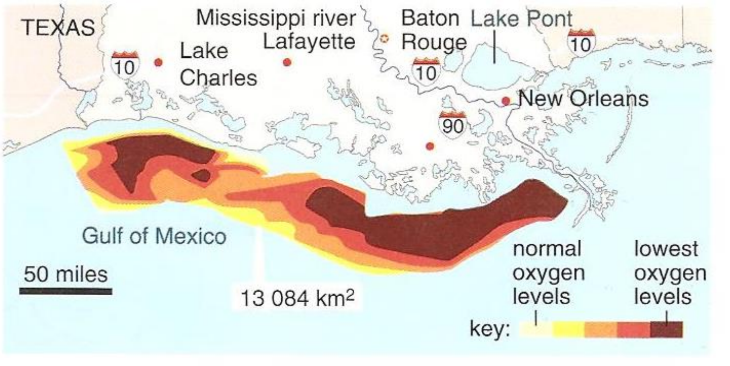
De visserij is erg belangrijk in de Golf van Mexico. Hier komt het grootste deel van de oesters en garnalen van de Verenigde Staten vandaan, evenals een aantal vissoorten. De dode zone kost het toerisme en de visserij jaarlijks $82 miljoen.

1. Leg uit hoe een dode zone zich vormt.

2. Waarom varieert de grootte van de dode zone van de Golf van Mexico elk jaar?

3. Waarom is de dode zone van de Golf van Mexico seizoenaal?

4. Verzin twee maatregelen om de grootte van de dode zone te verminderen.



Les 2.1 - Het gebruik van zeewier

Mensen oogsten al duizenden jaren zeewier. Hier zijn verschillende redenen voor:

- Voedsel: zeewier wordt in landen zoals Japan, Korea, IJsland en Wales veel gegeten. In Japan worden er meer dan 20 soorten zeewier als voedsel gebruikt, bijvoorbeeld in sushi. Zeewier is rijk aan eiwitten, vitaminen, mineralen zoals jood, en bevat weinig vet.

- Gels en emulgatoren: zeewier wordt gebruikt als een bron voor drie stoffen die gebruikt worden voor het maken van gels en emulgators.

o Alginaat: deze stof wordt uit zeewier gehaald en is een toegevoegde stof in voedsel zoals ijs en synthetisch kaviaar. Het wordt ook gebruikt in brandwondenpleisters en brandweerkleding

o Agar: dit wordt gebruikt om vegetarische gelei en agar platen voor microbiologie te maken

o Carrageenan: dit wordt gebruikt om voedsel met verschillende texturen te maken, zoals chocolademelk en chocoladerepen, omdat het helpt om de chocolade opgelost te krijgen

- Cosmetica en kruidenmedicijnen: zeewier extracten worden vaak gevonden in hydraterende crèmes en kruidenmedicijnen voor bijvoorbeeld artritis, tuberculose en verkoudheid.

De vraag naar zeewier heeft geleid tot de ontwikkeling van zeewierboerderijen in China en Japan. Zeewier wordt gezaaid op netten of touwen die worden neergelaten in een beschermd stuk water zoals een lagune. In de figuur zijn verschillende diepten waarop dit gebeurt weergegeven. Het gebruik van kunstmesten wordt hierbij afgeraden.

1. Leg uit hoe de toegenomen vraag naar zeewier geoogst in het wild problemen kan opleveren.

2. Leg uit waarom zeewier het best groeit bij waterdiepte 8.27b.

3. Met je kennis van het compensatiepunt, leg uit waarom zeewier dat in diep en warm water groeit, snel sterft.

4. Leg uit waarom het gebruik van kunstmest wordt afgeraden bij het groeien van zeewier.

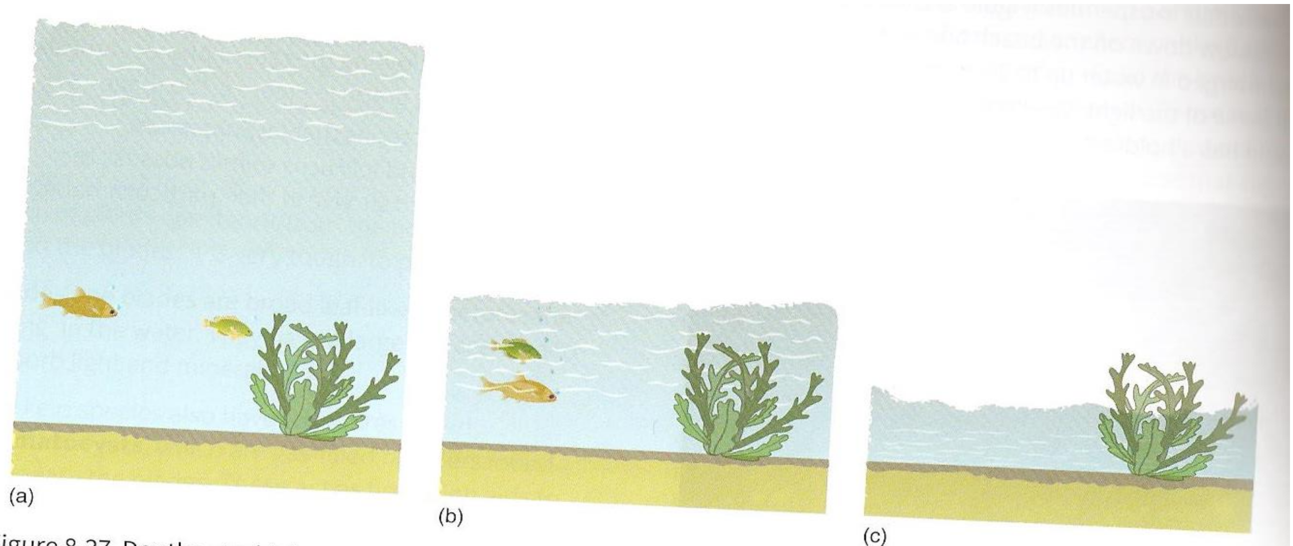


Figure 8.27. Depths at which seaweed might be planted.

Les 3 - Mariene algenbloeien en rode getijden

Algenbloeien zijn snelle, uitgebreide bloeien van fytoplankton en komen vaak voor in de oceanen. Sommige van deze bloeien zijn zo groot dat ze zichtbaar zijn vanuit de ruimte. Er zijn veel oorzaken: natuurlijk, seizoenaal, of door menselijke invloeden.

Een schadelijke algenbloei (Harmful Algal Bloom, HAB) is een algenbloei die een negatieve invloed heeft op andere organismen vanwege het produceren van gifstoffen. HABs hebben vooral effect op zeezoogdieren, zeeschildpadden, zeevogels en roofvissen. In het voorjaar van 2004 stierven tenminste 107 tuimelaars langs de kust van Florida omdat ze besmette vis met hoge concentraties van een algentoxine genaamd brevotoxine hadden binnengekregen. Brevotoxine wordt geproduceerd door de dinoflagellaat Karenia brevis, die regelmatig rode getijden veroorzaakt in de Golf van Mexico. Zeekoeien zijn ook doodgegaan door het eten van zeegras dat deze toxine bevatte. Veel voorkomende schadelijke effecten van HABs zijn:

- Productie van neurotoxines die vissen, zeevogels, zeeschildpadden en zeezoogdieren doden
- Menselijke ziekte of dood door het eten van besmette zeevruchten
- Stikken van dieren met kieuwen door blokkades van algen
- Dood van organismen door tekort aan zuurstof na het afbreken van dode algen

Vanwege de negatieve impact van HABs, worden deze goed in de gaten gehouden. Weerpatronen, seizoenen en menselijke vervuiling worden gebruikt om de vorming van algenbloeien te voorspellen zodat maatregelen zoals een verbod op zeevruchten kunnen worden genomen. Hierbij worden satellieten, water condities en observaties uit het veld gebruikt.

1. Leg uit waarom de algenbloei van Karenia brevis heeft geleid tot de dood van dolfijnen en zeekoeien in Florida.

2. Hoe kunnen HABs leiden tot verminderde zuurstof in het water waardoor vissen sterven?

3. Leg uit waarom de overheid zeevruchten consumptie zal verbieden als er een HAB wordt gesignaleerd.

4. Noem een korte termijn en lange termijn effect van HABs op de visserij.

5. Met je kennis van beperkende factoren, leg uit waarom een verhoogde koolstofdioxide concentratie in de atmosfeer kan leiden tot een toename in HABs.